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LLNL-CONF-414699

Pressure-Induced δ to α# Phase Transformations in a Pu-Ga Alloy

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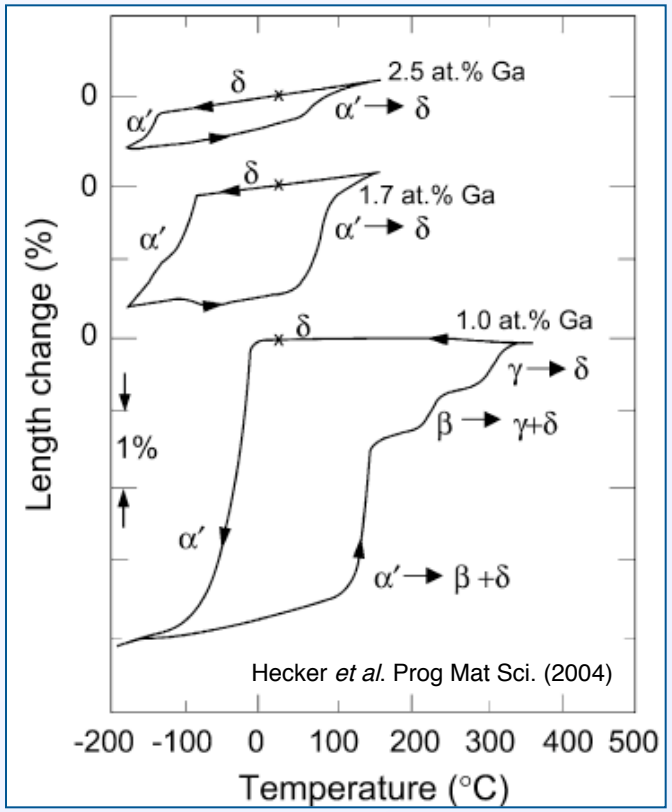
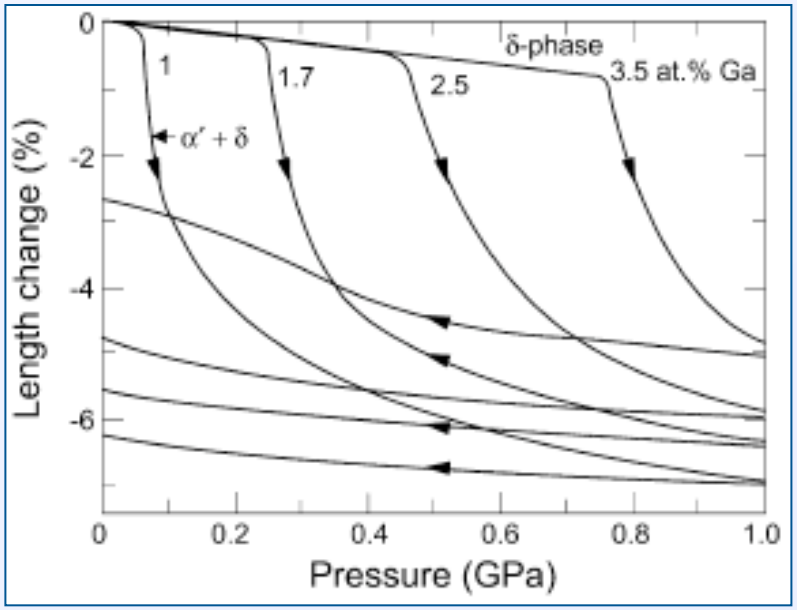
LLNL-CONF-xxxxxx

Understanding the phase transformations remains as one of the significant Pu metallurgical challenges

The δ → α′ isothermal martensitic transformation can be induced with continuous cooling experiments



Under pressure, Pu - Ga alloys transform directly to α′ and undergo either a direct (α′ → δ) or indirect (α′ → β′ + δ → γ′ + δ → δ) reversion

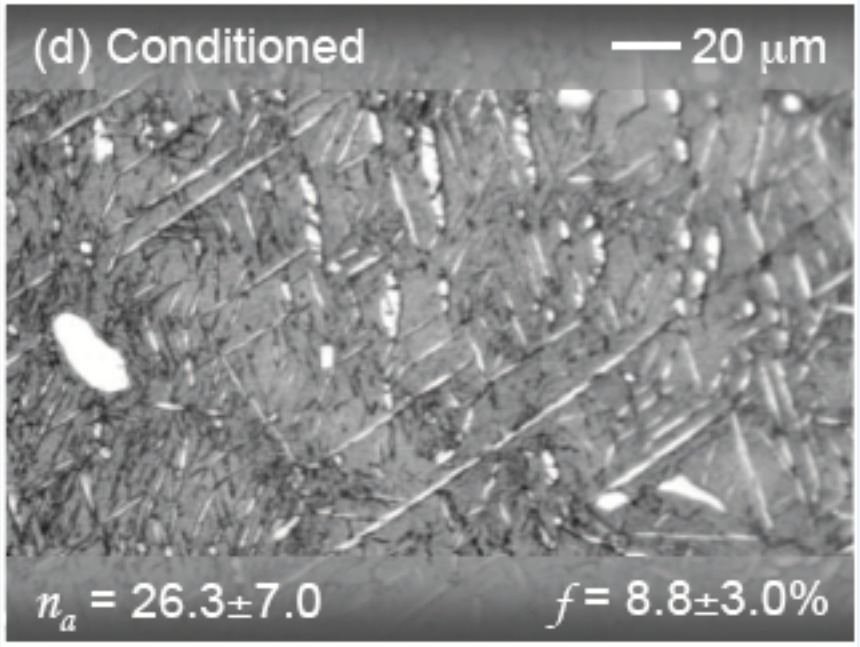


Hecker *et al.* Prog Mat Sci. (2004)

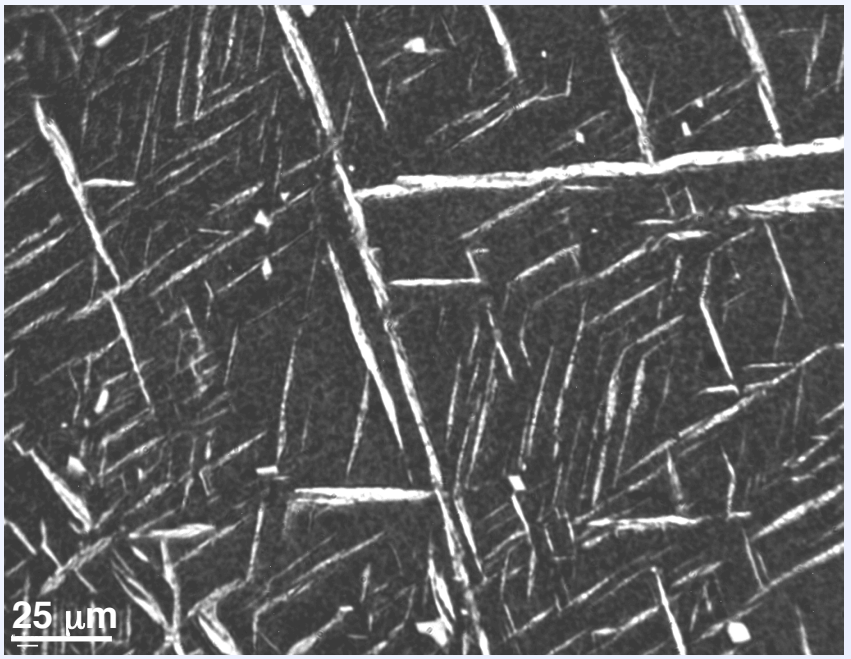
The α′ particles that form from the isothermal martensitic transformation appear as lathes in optical microscopy

Pu - 2.0 at.% Ga

-120°C/4 hours



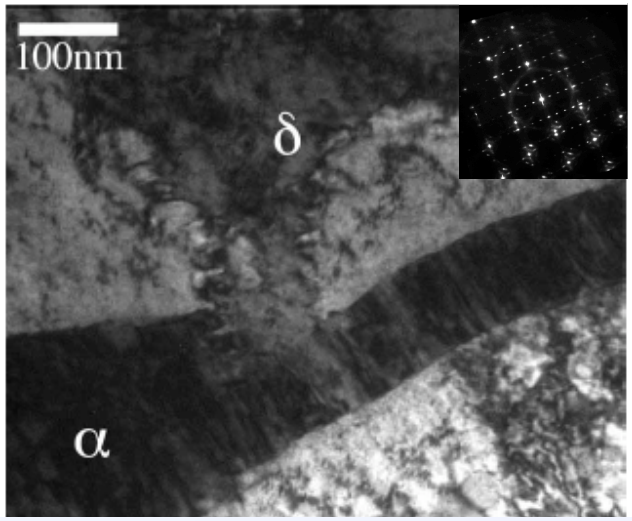
–155°C/4 hours

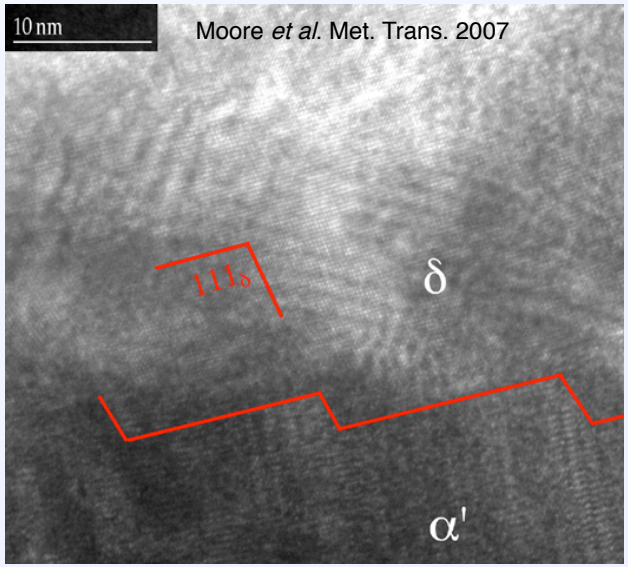


Partially transformed
(δ + α′ phases)

The δ → α′ isothermal martensitic transformation goes to ~ 25% completion

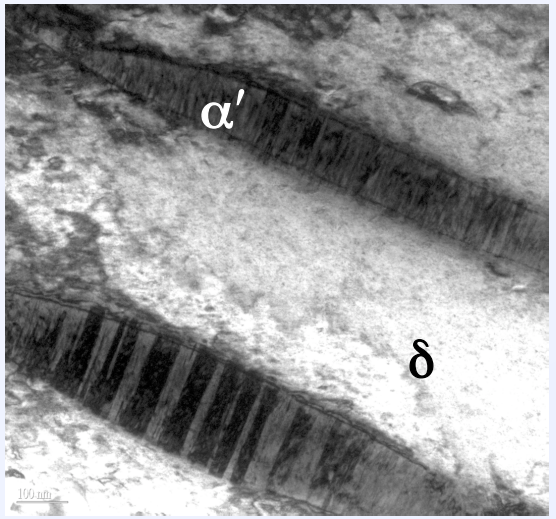
The crystallography and morphology of the δ → α′ transformation have been characterized with TEM

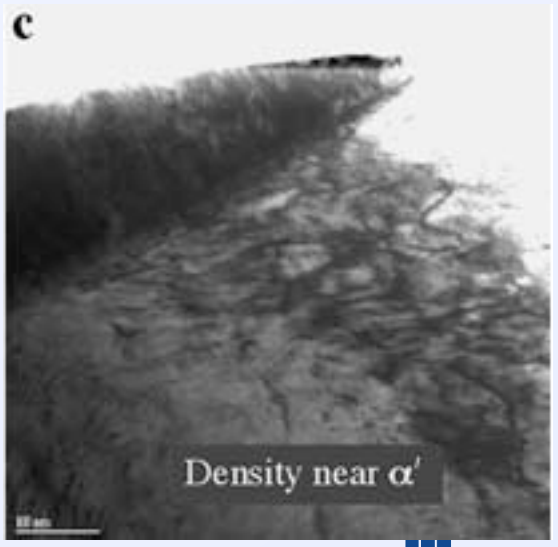




- The orientation relationship between α′ and δ is:
  $(111)_{\delta} \parallel (020)_{\alpha'}$
  $[-110]_{\delta} \parallel [100]_{\alpha'}$

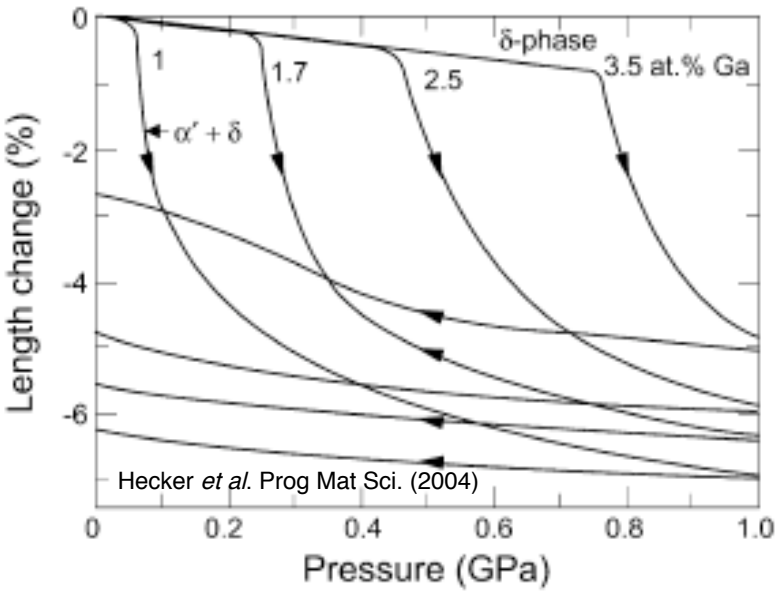
  (Zocco *et al.* Acta Met. 1990)
- α′ particles consist of 2 variants rotated 60° around $<020>_{\alpha'}$
- TEM shows $(205)_{\alpha\ni}$ twinning as a lattice invariant deformation mode
- The α′–δ interface is composed of a terrace and ledge structure that is faceted on 111_{δ}
- The dislocation density is ~ an order of magnitude greater in the vicinity of α′ particles





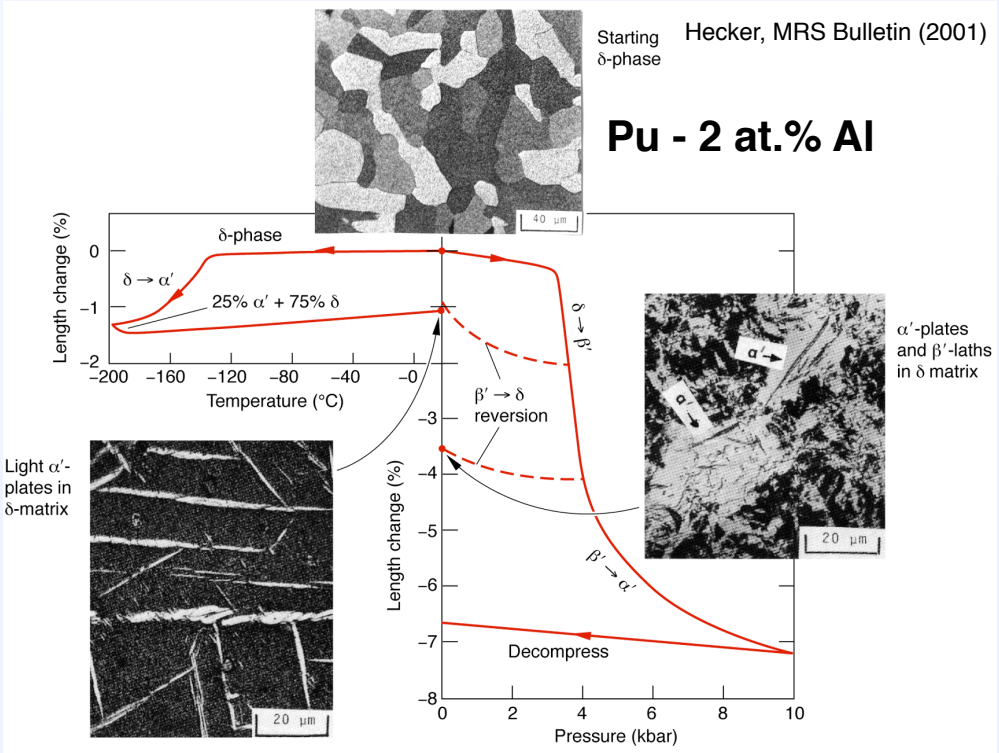
The δ → α′ transformation can also be induced by pressure

Pu - 2 at.% Ga



- **Under pressure, Pu - Ga alloys transform directly to α′ and undergo either a direct (α′ → δ) or indirect (α′ → β′ + δ → γ′ + δ → δ) reversion**
- **Reversion characteristics are similar to those in thermally-induced transformations**

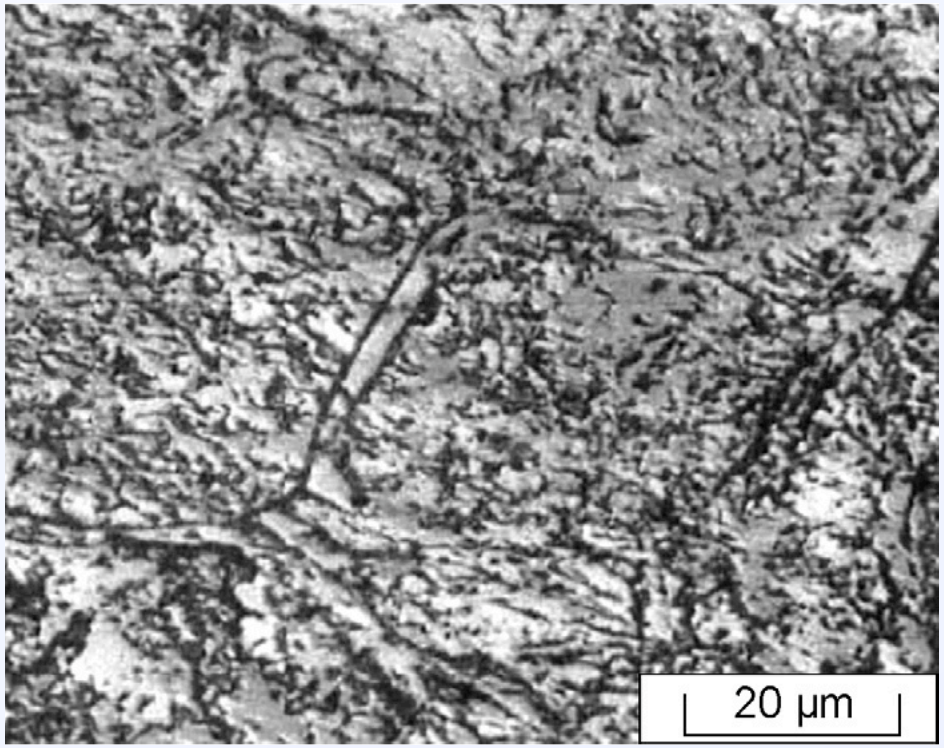
Pu - 2 at.% Al



Pu - 2 at.% Al alloy transforms first to β′ then to α′ under pressure

Upon cooling, Harbur reported that a 0.68 at.% Ga alloy has a density intermediate between δ and α phases

Harbur, JALCOM (2007)



After compressing to 1 GPa

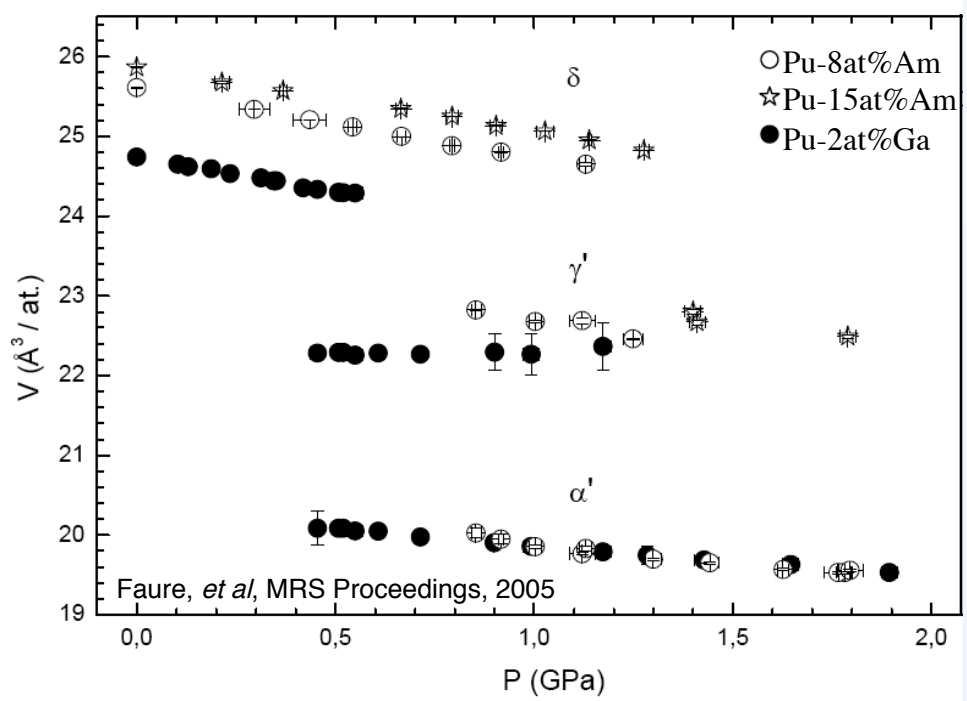
Alloy	% α′	% δ	% amorphous
1.0 at.% Ga	87	0	13
1.7 at.% Ga	66	0	34
2.5 at.% Ga	68	12	20

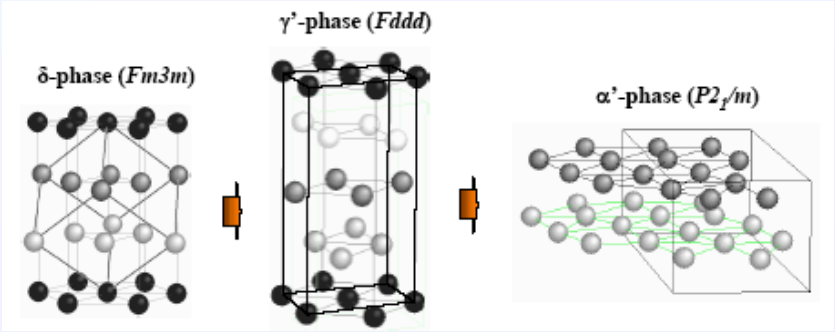
Harbur proposes that the δ phase transforms to α′ + amorphous phase

- **on cooling low solute alloys**
- **under pressure**

Harbur, JALCOM (2007)

Diamond anvil cell experiments on a Pu - 2 at.% Ga alloy reveal δ → γ′ → α′ transformation sequence



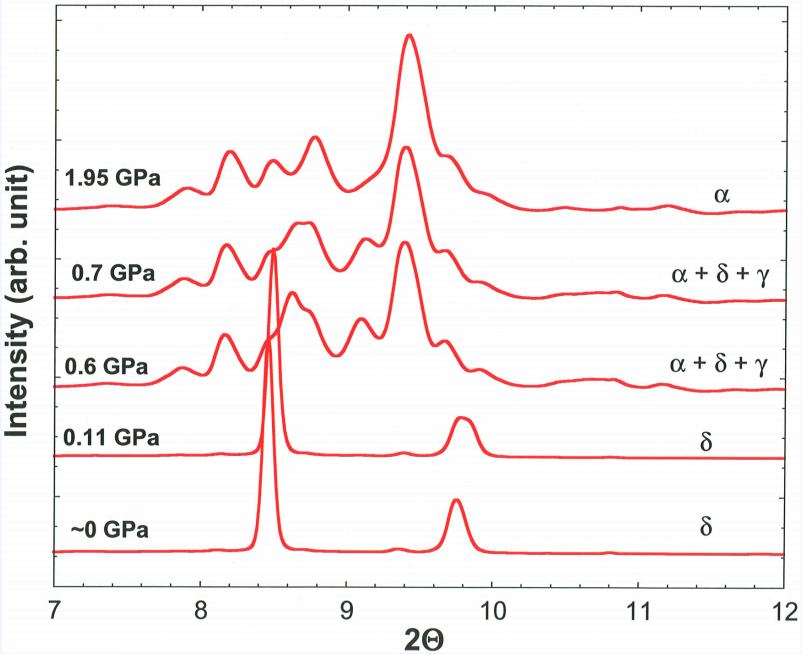


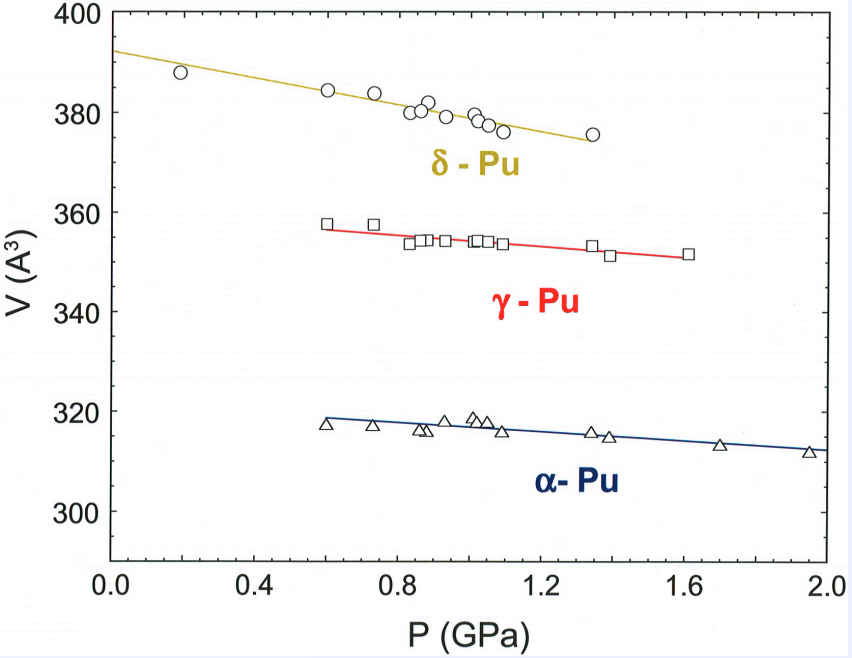
Faure *et al*. MRS Proceedings (2006)

In the DAC, Pu - 2 at.% Ga transforms through the sequence δ → γ′ → α′

Zukas *et al*. (1981) report Pu - 2 at.% Al alloys transform through the sequence δ → β′ → α′

Recent experiments at LLNL also suggest intermediate transitions between δ and α′





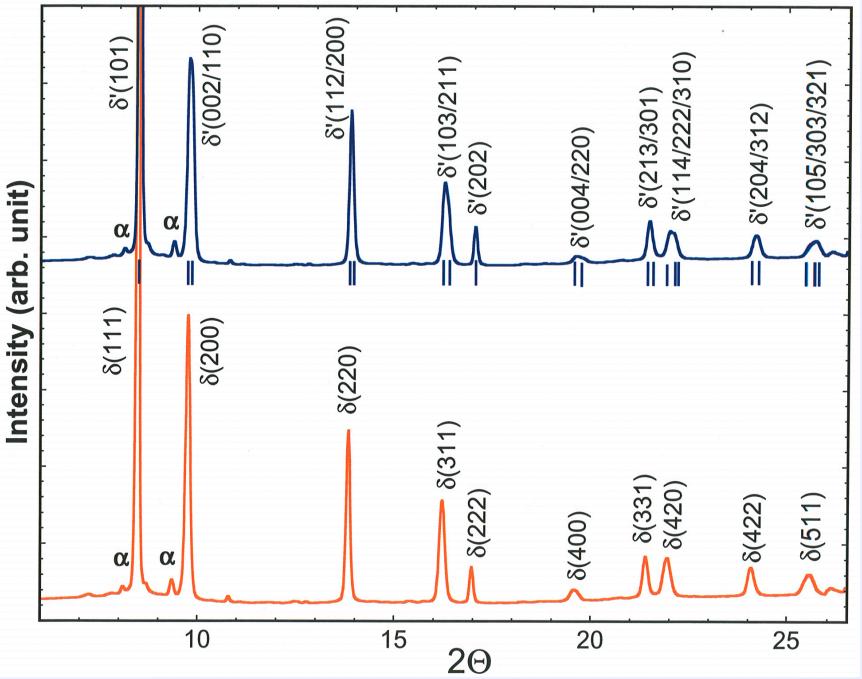
Schwartz *et al.* Prog Mat Sci. (2009)

- Diffraction peaks of the δ phase split at low pressures to a γ′ like structure
- γ′ like structure structure appears at ~0.6 GPa

- γ′ like structure structure disappears at ~1.6 Gpa

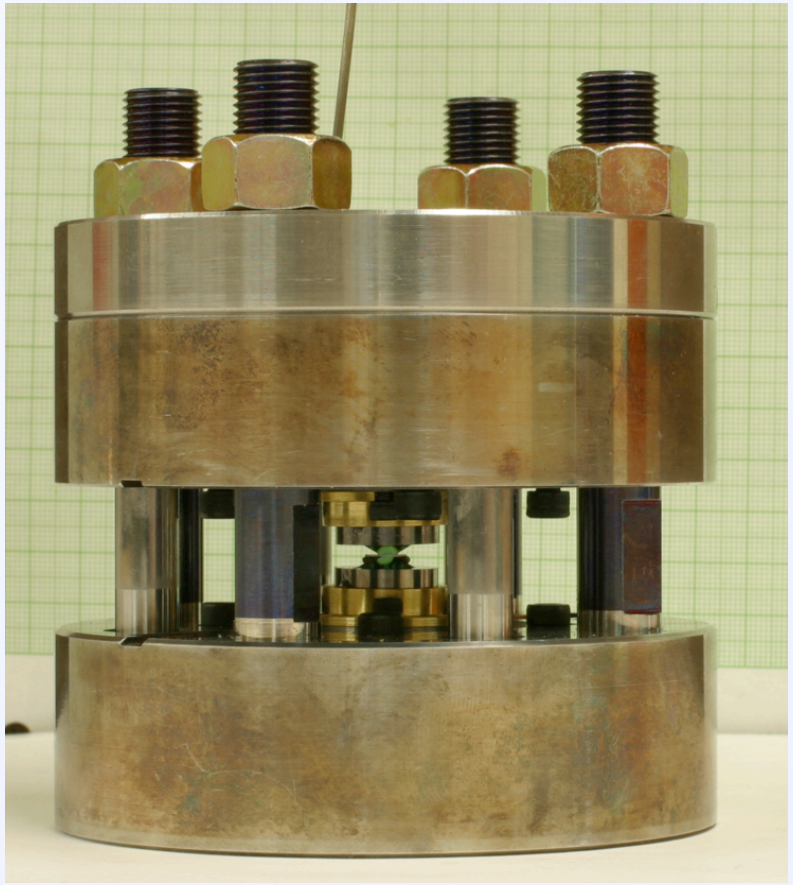
At low pressure, δ phase distorts to δ′

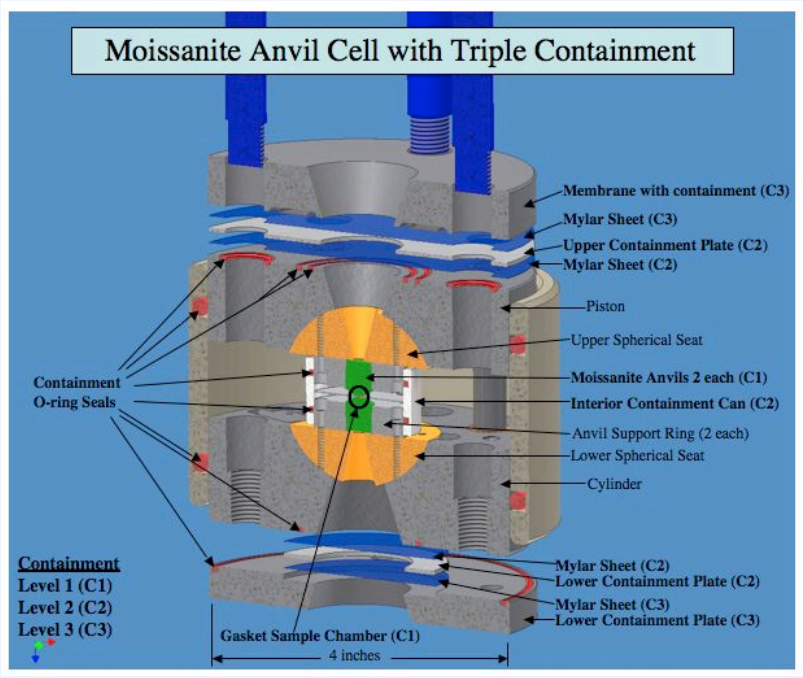
- Small amounts (<~1%) of γ′ and α′ coexist with δ at ambient
- Is identified at ~0.1 GPA
  - I4/mmm (S.G. 139, z = 2)
  - a = 3.240Å
  - c = 4.617Å
  - V = 48.47Å3 (0.2% denser than δ -Pu
  - Pressure induces growth of γ′ and α′



Schwartz *et al.* Prog Mat Sci. (2009)

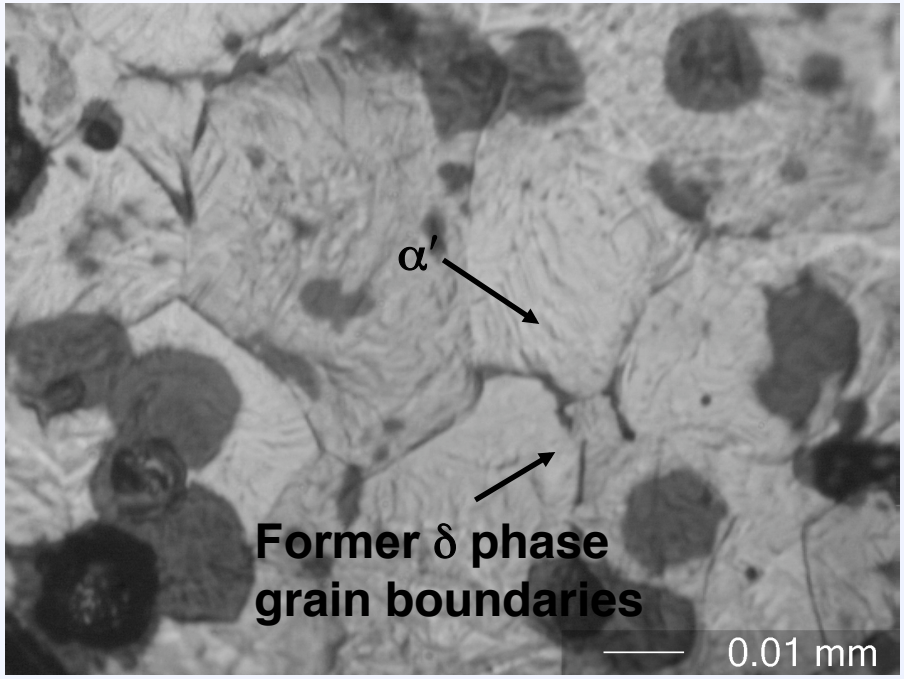
We are coupling low pressure recovery experiments with TEM to elucidate the mechanism and morphology

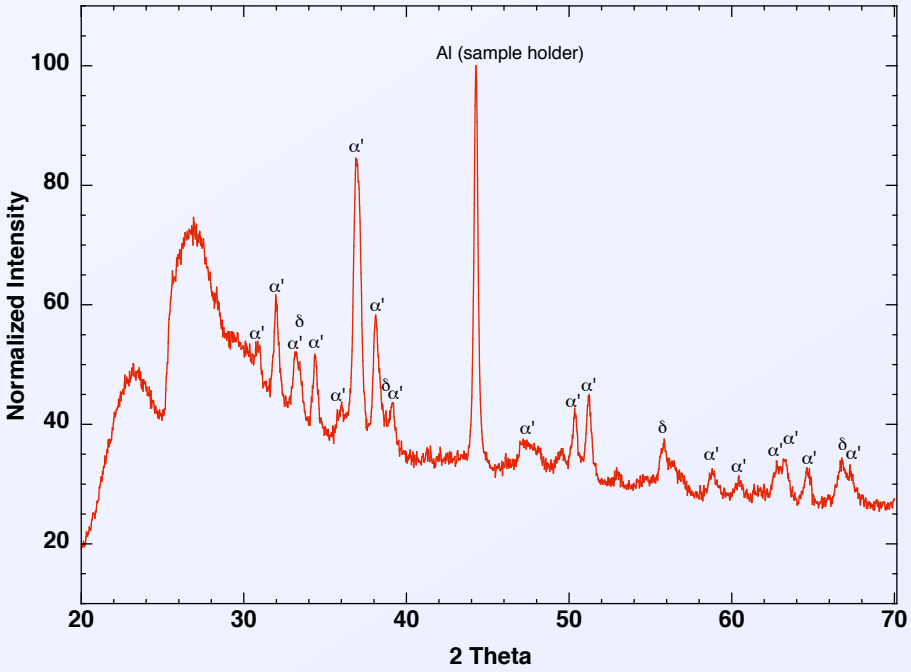




2.3 mm diameter specimens are slowly compressed to 1 GPa in the large volume moissanite anvil cell

Optical microscopy and x-ray diffraction of the compressed specimen reveals α′ and δ phases

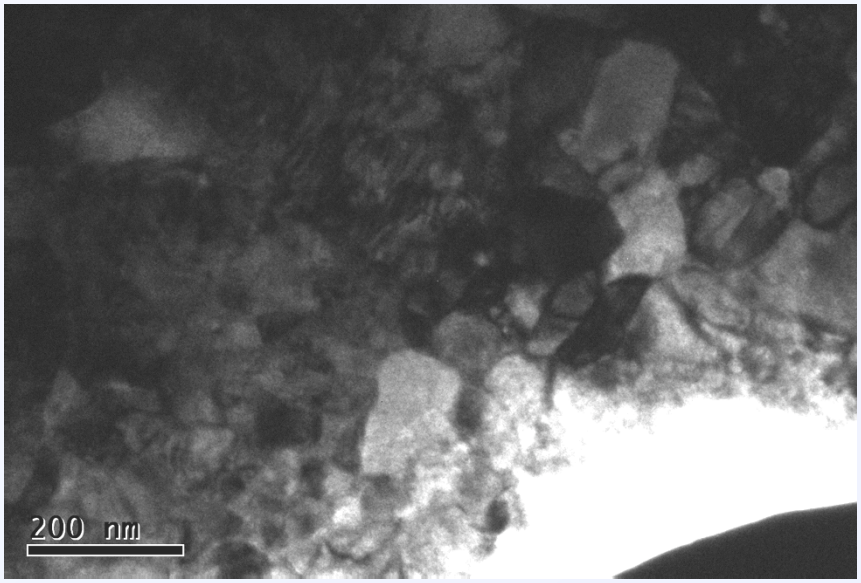


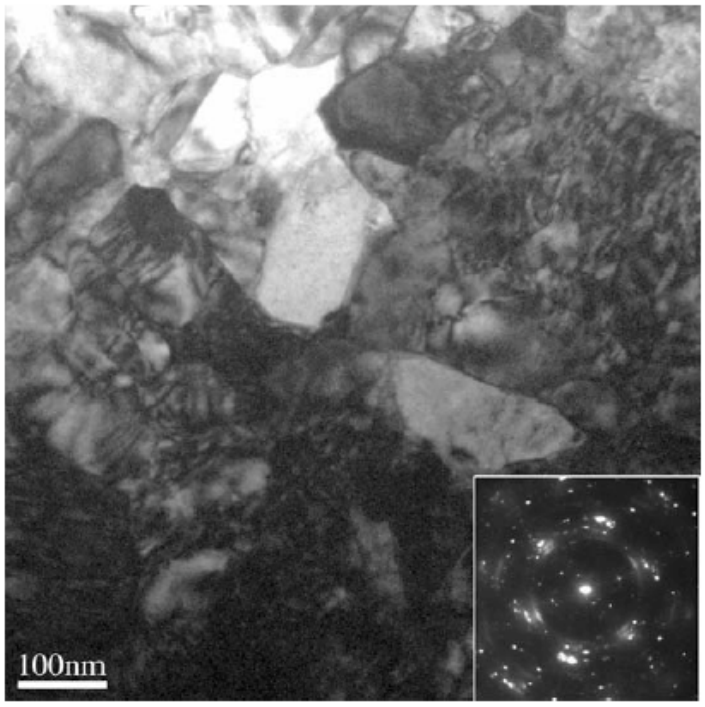


Optical microscopy does not have the resolution to differentiate between phases

X-ray diffraction experiments and simulations do not indicate the presence of an amorphous phase

The pressure-induced microstructure does not exhibit typical martensitic features

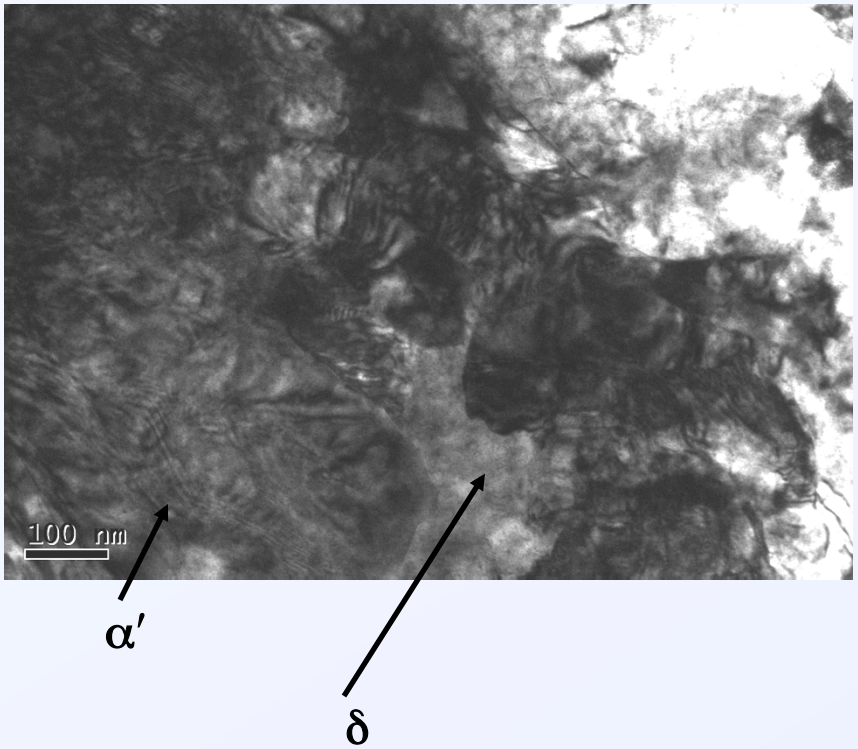


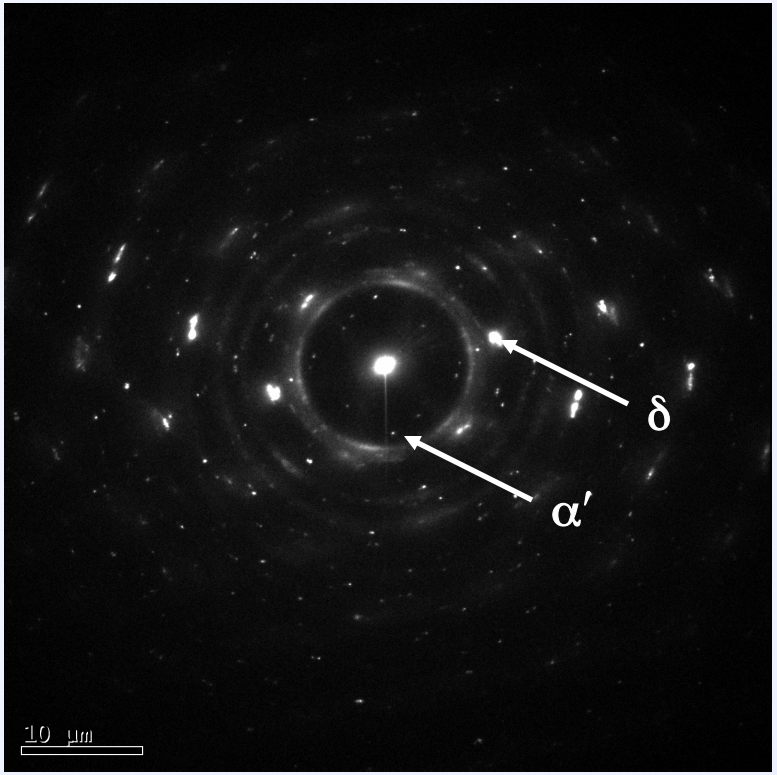


Pressure-induced δ → α′ transformation
- **Average α′ grain size ~ 100s nm, 10 – 20% δ**
- **Implies nucleation-dominated mechanism**

Low-temperature-induced δ → α′ isothermal martensitic transformation
- **Average α′ particle size ~ 1000s x 10,000s nm**
- **Implies nucleation-limited mechanism (strain)**

Preliminary TEM reveals fine-grained α′ and small amounts of δ – no evidence of an amorphous phase





10 – 20% δ phase is observed dispersed between the α′ grains
- **High dislocation density**
- **No apparent orientation relationship (yet)**

The isothermal martensitic and pressure-induced microstructures differ significantly

- **Low temperature isothermal δ → α′ transformation**
  - Nucleation is limited
  - Lath-shaped particles form
  - Intermediate phases are possible
- **Pressure-induced δ → α′ transformation**
  - Nucleation dominates
  - Very fine grain size results
  - No evidence of the amorphous phase
  - Intermediate phases are likely